Characteristics of Vaporizing Cryogenic Sprays for Rocket Combustion Modeling

Robert D. Ingebo
Lewis Research Center
Cleveland, Ohio

National Aeronautics and
Space Administration

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CHARACTERISTICS OF VAPORIZING CRYOGENIC SPRAYS FOR ROCKET COMBUSTION MODELING

Robert D. Ingebo
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, OH 44135

ABSTRACT

Experimental measurements of the volume-median drop diameter, $D_{v.5e}$, of vaporizing cryogenic sprays were obtained with a drop size measuring instrument developed at NASA Lewis Research Center. To demonstrate the effect of atomizing-gas properties on characteristic drop size, a two-fluid fuel nozzle was used to break up liquid-nitrogen, LN_2, jets in high-velocity gasflows of helium argon and gaseous nitrogen, GN_2. Also, in order to determine the effect of atomizing-gas temperature on specific surface-areas of LN_2 sprays, drop size measurements were made at gas temperatures of 111 and 293 K.

NOMENCLATURE

a   acceleration, cm/sec^2

Cd   drag coefficient

Do   liquid jet diameter, cm

$D_{v.5}$ volume median drop diameter, cm

k_c correlation coefficient for Eq. (6)

k_e correlation coefficient for Eq. (1)

Nu   Nusselt number, based on $D_{v.5e}$

n   exponent for Eqs. (1) and (6)

Re   Reynolds number, based on $D_{v.5e}$

To   ambient airflow temperature, K

t   vaporization time, sec

Vc   acoustic velocity, cm/sec

W   weight flow of fluid, g/sec

We   Weber number, based on $D_{v.5e}$

x   axial downstream sampling distance

μ absolute viscosity, g/cm sec

ρ fluid density, g/cm

Subscripts

c   calculated

e   experimental

g   gaseous nitrogen, GN_2

l   liquid nitrogen, LN_2

o   orifice

INTRODUCTION

Highly volatile LN_2 sprays, with relatively large surface area per unit volume, were produced with a multiphase flow fuel nozzle. Such fuel sprays are desirable since they produce rapid fuel vaporization and efficient combustion in gas-turbine and rocket combustors. How atomizing-gas and liquid-jet properties effect the spray characteristic dropsize needs to be determined mathematically in

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order to compute changes in spray surface-area with residence time in the combustor. Mathematical expressions of this nature were investigated in the present study and used to correlate volume-median diameter, $D_{v.5c}$, with atomizing-gas mass flux and temperature. Such information is needed in the development of fuel spray combustion models that are based on characteristic drop-size expressions and cover wide ranges of liquid fuel and atomizing-gas properties. The resulting combustion models can then be used to develop more efficient fuel nozzles that will improve combustor performance and reduce exhaust emissions.

In the present investigation of vaporizing LN_2 sprays, measurements of $D_{v.5c}$ were made in the presence of relatively high thermal gradients. Atomizing-gas temperatures were 111 and 293 K and LN_2 droplet surface temperatures were near the boiling point of LN_2, 77 K. As a result, relatively high heat-transfer rates occurred across the gas film and they were considerably higher than those encountered in the study of water sprays, as described in Ref. 1. In that study, the effect of vaporization on drop size measurements was negligible when measurements were made very close to the fuel nozzle orifice. However, in the present study of LN_2 sprays, small droplets vaporized very fast and it was necessary to compute the effect of droplet vaporization on drop size measurements. Thereby, it was possible to determine values of $D_{v.5c}$ for unvaporized cryogenic sprays produced at the fuel nozzle orifice.

Multiphase flow atomization of LN_2 jets in sonic velocity He, Ar and GN_2 gasflows was experimentally investigated with the scattered-light scanner shown in Fig. 1. Sonic velocity gasflows were used so that liquid jet breakup occurred primarily in the regime of aerodynamic stripping. As a result of using high-velocity gasflow, very small LN_2 droplets were rapidly and completely formed at the fuel nozzle orifice. If the low gas-velocity regime of capillary wave breakup had been studied, then ligaments would have been formed and only partial breakup of the LN_2 jets would have occurred at the fuel nozzle orifice. Heat-transfer and drag coefficients obtained from earlier studies of droplet vaporization in

high-velocity gasflow, Ref. 2, were used in the present study to calculate LN_2 droplet acceleration and vaporization rates.

Numerous investigators, as reported in Refs. 1 to 7, have studied the effects of atomizing-gas mass flux and gas velocity on spray drop size. As a result, different effects of atomizing-gas velocity on the characteristic drop size, Dc, have been observed as shown in table I. For the expression $Dc \sim V^n$, the exponent n determined by various investigators varied from −1.00 to −1.33. Atomization theory predicts $n = -1.33$ for liquid jet breakup in high-velocity gasflow. The disagreement between various investigators could to some extent be attributed to the effect of droplet vaporization on drop size measurements, especially when measurements were taken at distances relatively far downstream of the atomizer. This occurred, as reported in Ref. 1, when sampling distances downstream of the atomizer were increased from 2.2 to 6.7 cm. In that case, the exponent for atomizing-gas velocity decreased from −1.33 to 1.00.

A scattered-light scanner developed at NASA Lewis Research Center by Buchele, Ref. 8, was used to measure the volume-median diameter, $D_{v.5e}$, of LN_2 sprays formed in high-velocity He, GN_2 and Ar gasflows at atomizing-gas temperatures of 111 and 293 K. Sprays were sampled at a distance of 2 mm downstream of the fuel nozzle to minimize losses of very small droplets due to vaporization. Values of $D_{v.5e}$ varied from 3 to 30 μm.

APPARATUS AND PROCEDURE

Multiphase flow atomization of LN_2 jets in high-velocity gasflows of He, GN_2 and Ar was investigated at atomizing-gas temperatures of 111 and 293 K. A two-fluid fuel nozzle was used as shown in Fig. 1. It was mounted at the center line of a 24 cm diameter duct and operated over pressure ranges of 0.2 to 1.0 MPa for both fluids, i.e., LN_2 and the atomizing gases. The LN_2 sprays were injected downstream into the atmosphere at the duct exit. The center of the 4.4 × 1.9 cm laser beam was located at a distance of 1.2 cm downstream of the atomizer orifice. Figure 2 shows details of the fuel nozzle. At a temperature of 77 K, LN_2 was injected into the airflow by gradually opening a control valve until the desired flowrate of 51 g/sec was obtained, as indicated by a turbine flow meter. To breakup the jet, an atomizing gas was turned on and the mass flowrate was measured with a 0.51 cm diameter sharp-edge orifice.

The scattered-light scanner optical system is shown in Fig. 3. It consisted of a laser beam expander with a spatial filter, rotating

Figure 1.—Apparatus and auxiliary equipment.

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Two-fluid fuel nozzle

TABLE I.—ATOMIZING-GAS
VELOCITY EXPONENT, n, FOR
LIQUID JET BREAKUP IN HIGH-
VELCOITY GASFLOW

Source	Exponent, -n
Adelbert, Theory[13]	1.33
Present study, x = 2.2 cm	1.33
Kim and Marshall[3]	1.14
Lorenzetto and Lefevbvre[4]	1.00
Nukiyama and Tanasawa[5]	1.00
Weiss and Worsham[6]	1.33
Wolf and Anderson[7]	1.33

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scanning-slit and a detector. The instrument measures scattered light intensity as a function of scattering angle by repeatedly sweeping a variable-length slit in the focal plane of the collecting lens. Scattered-light energy data were obtained as a function of scattering angle relative to the laser beam axis. The method is similar to that described in Ref. 9. As recommended by studies made in Ref. 8, measurements of scattered-light energy were normalized by the maximum energy and plotted against scattering angle, in order to determine the volume median diameter, $D_{v.5e}$. Also, it should be noted that this method can be used independent of particle size distribution function. In making a typical drop size measurement, the scan is repeated 60 times per second. This averages out any temporal variations in the energy curve. By measuring $D_{v.5e}$ for the entire droplet cloud, spray pattern effects were minimized.

The scattered-light scanner was calibrated with five sets of monosized polystyrene spheres having diameters of 8, 12, 25, 50 and 100 μm. The sprays were sampled very close to the fuel nozzle orifice, i.e., 2 mm downstream of the nozzle. As a result,
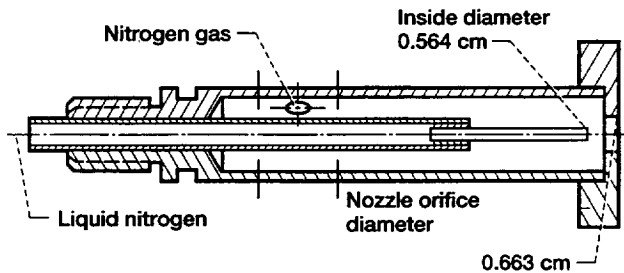

Figure 2.—Diagram of pneumatic two-fluid atomizer.

the LN_2 sprays contained relatively high number-densities of very small droplets and drop size measurements required correction for multiple scattering as described in Ref. 10. Also, the measurements were corrected to include Mie scattering theory, when very small drop diameters, i.e., 10 μm or less were measured. Reproducibility tests of the drop size data gave an agreement of ±5 percent. The effect of gas-density gradients on characteristic drop-size measurements was avoided by obtaining new background readings at each gasflow condition when the atomizing-gas temperature, Tg, was 111 K and 422 K. At Tg = 293 K, the background reading remained constant when gas flowrate was varied, since the ambient airstream temperature was also 293 K.

EXPERIMENTAL RESULTS

Effects of atomizing-gas properties on experimental measurements of $D_{v.5e}$ were investigated. The entire spray cross section was sampled with the downstream edge of the laser beam located at a distance of 2.2 cm downstream of the fuel nozzle orifice, as shown in Fig. 3. Small LN_2 droplets were partially vaporized as they passed through the 2 cm scattered-light scanner laser beam and some of the very small droplets were completely vaporized before they could exit the beam. As a result, experimental measurements of drop size could only be obtained for partially vaporized LN_2 sprays. Therefore, the change in dropsize, $\Delta D_{v.5c}$, was calculated by using previously obtained, Ref. 2, vaporization rate expressions. It was then used to compute the initially unvaporized spray drop size, $D_{v.5c}$, that had been formed at the fuel nozzle orifice.
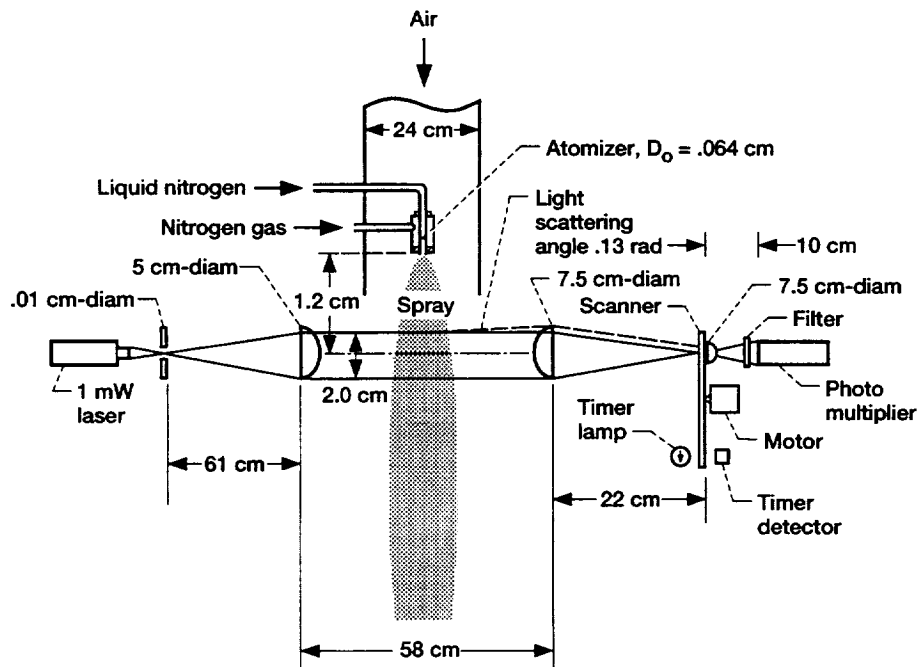

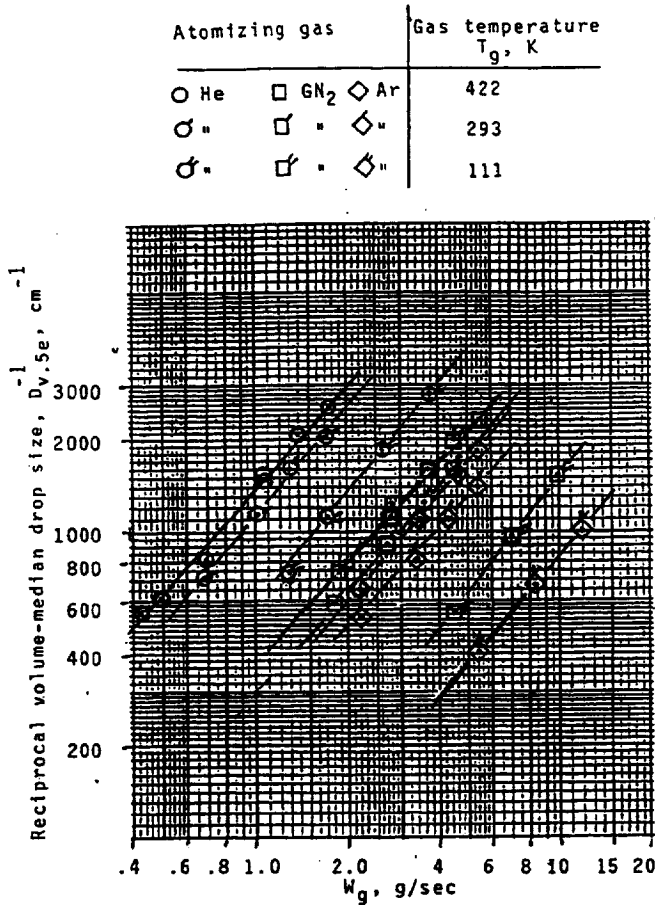Figure 3.—Atmospheric pressure test section and optical path of scattered-light scanner.

Atomizing gas			Gas temperature T_g, K
O He	□ GN_2	◇ Ar	422
♂ "	◘ ▪	◆ "	293
♂ ▪	◘ ▪	◆ "	111

Figure 4.—Variation of experimentally determined volume-median drop size, $D_{v.5e}$, with atomizing-gas flowrate, W_g.

Atomizing-Gas Flowrate Effects On $D_{v.5e}$

Effects of atomizing-gas flowrates and the physical properties of He, GN_2 and Ar on $D_{v.5e}$ were investigated. Sonic velocity gasflows were used to atomize LN_2 jets. A plot of atomizing gasflow, W_g, against reciprocal values of $D_{v.5e}$ is shown in Fig. 2. From this plot, the following general expression was obtained:

$$D_{v.53}^{-1} = k_e W_g^n \qquad (1)$$

where $k_e = 1125$, 275 and 222 and n = 1.10, 1.11 and 1.08 for the atomizing gases He, GN_2 and Ar, respectively, at a gas temperature of 293 K. Values of $D_{v.5e}$ and W_g are given in cm and g/sec, respectively.

Experimental values of the exponent n varied slightly, from 1.08 to 1.11 and they were considerably below the value of n = 1.33 as predicted by atomization theory and reported in Ref. 13, for the breakup of liquid jets in high-velocity gasflow. This discrepancy between experimental and theoretical values of exponent n is attributed to the complete vaporization of very small and highly volatile LN_2 droplets and incomplete vaporization of the relatively large LN_2 drops. This occurred before dropsize measurements could be completed with the scattered-light scanner. Therefore, in
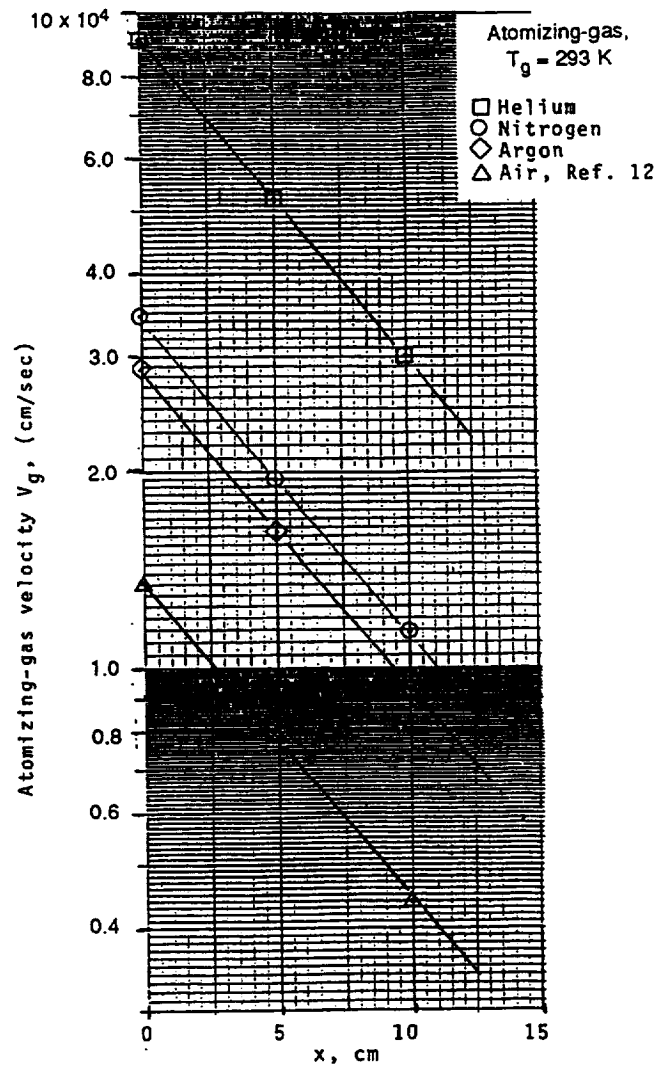

Figure 5.—Deceleration of atomizing-gases downstream of fuel-nozzle orifice. At x = 0, $V_g = V_c$.

the present study, the effect of droplet vaporization on drop size measurements of highly volatile LN_2 sprays is recognized. In Ref. 11, this effect was not accounted for when the drop size data were analyzed. As a result, even though effect of atomizing-gas flowrate on $D_{v.5e}$ did appear to agree with theory, it is apparent now that the proportionality constant k_e was too low to be used in determining the characteristic dropsize of an initially unvaporized cryogenic spray.

Droplet Acceleration and Vaporization Time

Effects of LN_2 droplet vaporization rates on $D_{v.5e}$, in high-velocity gasflows, were determined by calculating vaporization time, t, as based on drop velocity, Vd, for a given characteristic dropsize. Time, t, was calculated over a distance of 2.2 cm, i.e., from nozzle orifice to the downstream edge of the laser beam, as shown in Fig. 3. Values of Vd and acceleration, a, for LN_2 droplets were calculated according to the following momentum balance, as given in Ref. 8:

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$$Md\ a = 1/2\ Ad(Vg - Vd)^2 Cd \qquad (2)$$

where Md and Ad are mass and area of drop size $D_{v.5e}$, respectively. Also, $Md = \rho_2 \pi\ D^3_{v.5e/6}$ and Cd is the drag coefficient based on characteristic length, $D_{v.5e}$.

Rewriting Eq. (2) in terms of incremental changes in Vd over a distance Δx, gives the following relationship:

$$\frac{\Delta V^2 d}{\Delta x} = \frac{3(Vg - Vd)Cd}{2\ D_{v.5e}} \qquad (3)$$

where $Cd = 27\ Re^{0.84}$, as given in Ref. 2 and Re is based on the characteristic drop size, $D_{v.5e}$.

The atomizing gases He, GN_2 and Ar decelerated into low-velocity airflow and gas velocity at the nozzle orifice was equal to the acoustic velocity of the gas. Values of Vg used to solve Eq. (3) were calculated at downstream distances of 5 and 10 cm, respectively, and are plotted in Fig. 5. Values of Vg based on data given in Ref. 12 are plotted in Fig. 5 for comparison. The percent deceleration of the atomizing gases was assumed to be approxi-

mately the same as that observed in Ref. 12, since similar two-fluid fuel nozzles were used in both studies.

Initial droplet velocity, V_d, was 2.55 m/sec., i.e., the injection velocity of the LN_2 jet. Acceleration of LN_2 droplets characterized by $D_{v.5e}$ were determined by numerically integrating Eq. (3) and plotting V_d against downstream distance, x, as shown in Fig. 6. From this plot, vaporization time t was calculated by means of the expression $t = x/V_d$. Values of t are given in table II, for Tg = 293 K, along with Reynolds numbers averaged over the distance x and values of $D_{v.5e}$. Atomizing-gas transport properties used in calculating vaporization times are given in table III, for Tg = 293 K.

TABLE II.—VAPORIZATION TIME, Δt, AND REYNOLDS NUMBER

Atomizing gas at Tg = 293 K	Wg, g/sec	$D^{-1}_{v.5e}$, cm^{-1}	$\Delta t \times 10^4$ sec	Re
Helium	1.00	1125	1.35	15.2
Nitrogen	4.54	1650	1.44	35.3
Argon	5.43	1370	1.52	31.4

Atomizing-gas flowrate, W_q, g/sec $D^{-1}_{v.5e}$, cm^{-1}

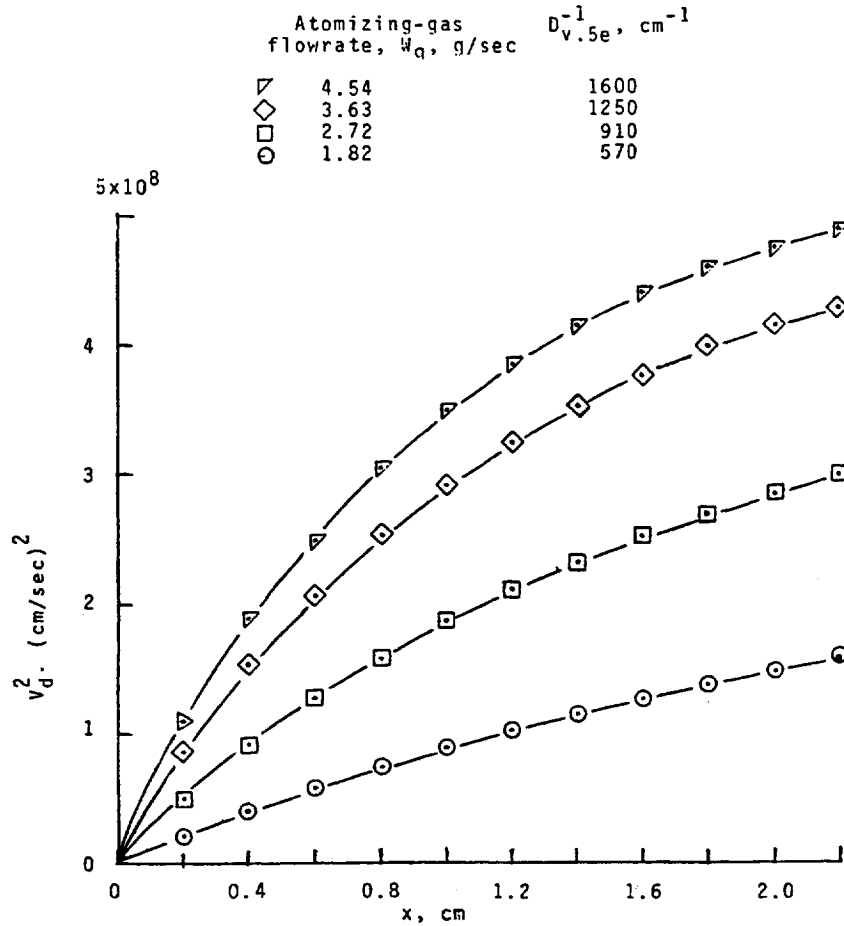|		
▽	4.54	1600
◇	3.63	1250
☐	2.72	910
⊙	1.82	570

Figure 6.—Acceleration of volume-median dropsize, $D_{v.5e}$, in nitrogen gasflow, at T_g = 293 K.

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TABLE III.—ATOMIZING-GAS TRANS-
PORT PROPERTIES; Tg = 293 K and
Wg = 4.54 g/sec

Atomizing gas	$Vc \times 10$, cm/sec	$\mu_g \times 10$, g/cm sec	$kf \times 10$, cal/sec sq cm, °C/cm
Helium	9.10	1.98	26.3
Nitrogen	3.43	1.25	4.2
Argon	2.87	1.10	2.85

Computation of Initial Characteristic Drop Size, $D_{v.5c}$

Vaporization rates of characteristic drop sizes of the cryogenic sprays were calculated according to the heat balance expression: dm/dt = hAΔT/Ht, where h is the heat transfer coefficient and A is spray surface-area based on $D_{v.5e}$. Also, ΔT = Tg − Td and Ht = Hv + CpΔT, where Hv is latent heat of vaporization of LN_2 and Cp is the specific heat of nitrogen vapor. The droplet vapor-

ization rate, i.e., the rate at which spray surface-area changes with time, was calculated from the following heat-balance expression:

$$\frac{-D_{v.5}^2}{\Delta t} = \frac{4kg\ \Delta t\ Nu}{\rho_g Ht} \qquad (4)$$

where kg and ρ_g are gas thermal conductivity and liquid density, respectively. Previous studies of fuel droplet vaporization, as reported in Ref. 2, used a high-speed droplet tracking camera to determine vaporization rates of jet-A fuel, n-octane, water and several other liquids. As a result, the following expression was obtained: Nu + 2 + 0.303 Re, where Nu is Nusselt number and Re = $D_{v.5e}$ $\rho_g V_r / \mu_g$. V_r is gas velocity relative to drop velocity, which is averaged over the incremental distance Δx. Atomizing-gas viscosity and thermal conductivity were evaluated at the average gas-film temperature. LN_2 temperature was kept at near the boiling point 77 K, i.e. sufficiently low to avoid flash boiling of the liquid jet. Latent heat of vaporization of LN_2 and the specific heat of the nitrogen vapor were evaluated at 77 K and the average gas-film temperature, respectively.
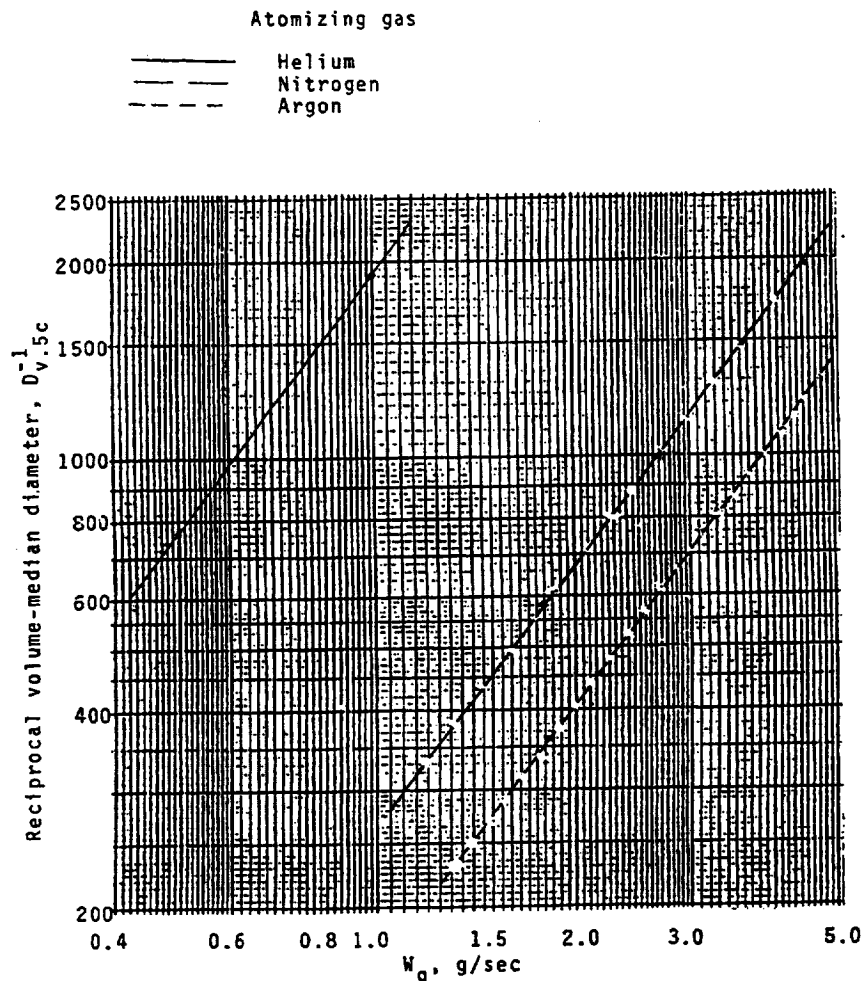
Atomizing gas

——————— Helium
—— —— Nitrogen
—— —— —— Argon

Figure 7.—Effect of W_g on initially unvaporized $D_{v.5c}$, at fuel-nozzle orifice, x = 0, and T_g = 293 K.

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Values of the initially unvaporized volume median diameter squared, $D_{v.5c}^2$, were calculated from experimental measurements of $D_{v.5e}^2$ and values of $-\Delta D_{v.5}$ were obtained from Eq. (4), as follows:

$$-\Delta D_{v.5}^2 = D_{v.5c}^2 - D_{v.5e}^2 \qquad (5)$$

Values of $D_{v.5c}$ were correlated with atomizing-gas flowrate, W_g, as shown in Fig. 7 and the following general expression was obtained:

$$D_{v.5c}^{-1} = kc \, W_g^{1.33} \qquad (6)$$

where $k_c = 264$ for GN_2 at 293 K. For the same conditions, the experimental value of ke obtained from Eq. (1) was 275. Thus, values of k_c and k_e were nearly the same. However, the value of exponent n for partially vaporized sprays is considerably less, i.e., 1.11 as compared with 1.33 given in Eq. (6). This shows a marked effect of droplet vaporization on drop size measurements. Also, Eq. (6) shows good agreement of calculated values of n with atomization theory, i.e., Ref. 13 predicts n = 1.33 for liquid jet breakup in high-velocity gasflow. As a result of using heat-transfer and drag coefficient expressions reported in Ref. 2, it was possible to compute values of characteristic drop size $D_{v.5c}$ for unvaporized LN_2 sprays formed at the fuel injector orifice.

Correlation of $D_{v.5c}$ with Dimensionless Groups

$D_{v.5c}$ was normalized with respect to LN_2 jet diameter, Do, and plotted against the product of We, Re and $\rho g/\rho l$, i.e., the Weber number, Reynolds number and fluid-density ratio, respectively, as shown in Fig. 8. This plot yields the following expression:

$$Do/D_{v.5c} = kc(WeRe \, \rho g/\rho l)^{0.44} \qquad (7)$$

where WeRe is the ratio of aerodynamic to liquid surface forces, i.e., LN_2 viscosity and surface tension. The three lines in Fig. 8 show, that the effect of physical properties of the three atomizing gases on k_c, needs to be determined to obtain a single correlating expression based on Eq. (7).

Atomizing-Gas Property Effects on LN_2 Jet Breakup

In Ref. 14, a series of tests were made using He, GN_2 and Ar as atomizing gases to study the effect of atomizing-gas properties on LN_2 jet breakup at a gas temperature of 293 K. As a result of this study, a new dimensionless group was derived that gave the effect of rms gas molecular-velocity, Vm, and gas viscosity, μg, on $D_{v.5c}$, as shown by the following relationship:

$$Do/D_{v.5c} \sim (\rho l Vm^3/g\mu g)^{0.75} \qquad (8)$$

Atomizing-gas,
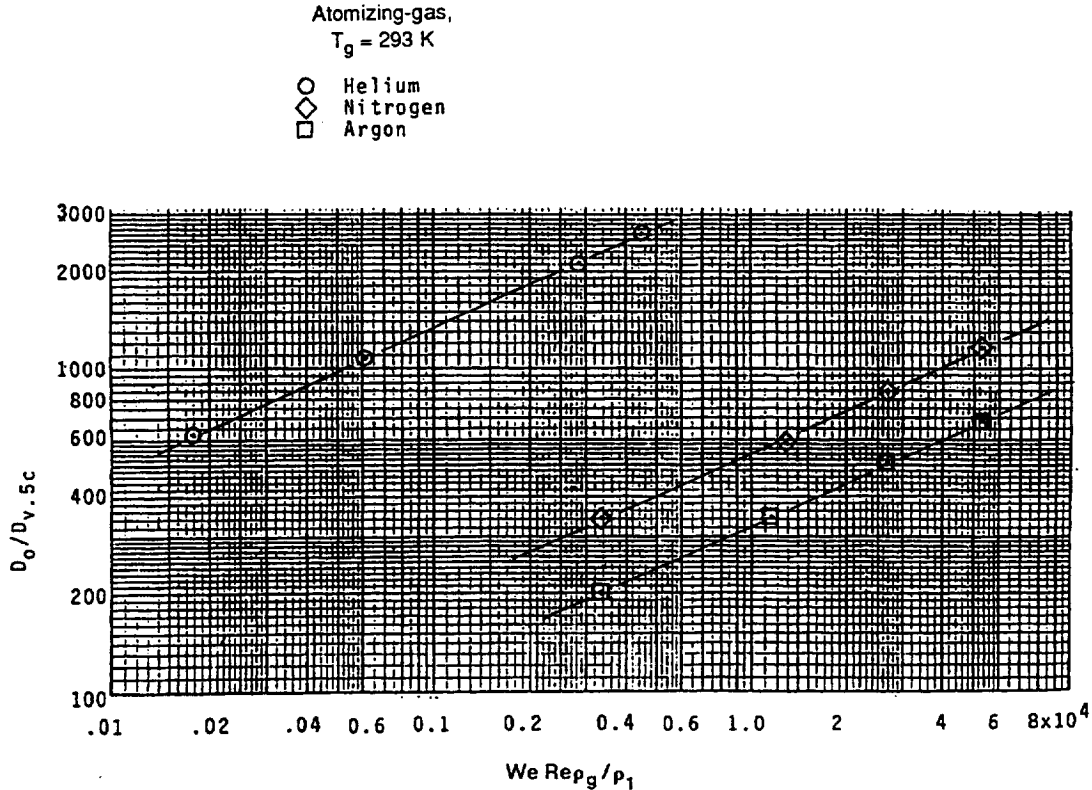$T_g = 293$ K

  O Helium
  ◇ Nitrogen
  □ Argon

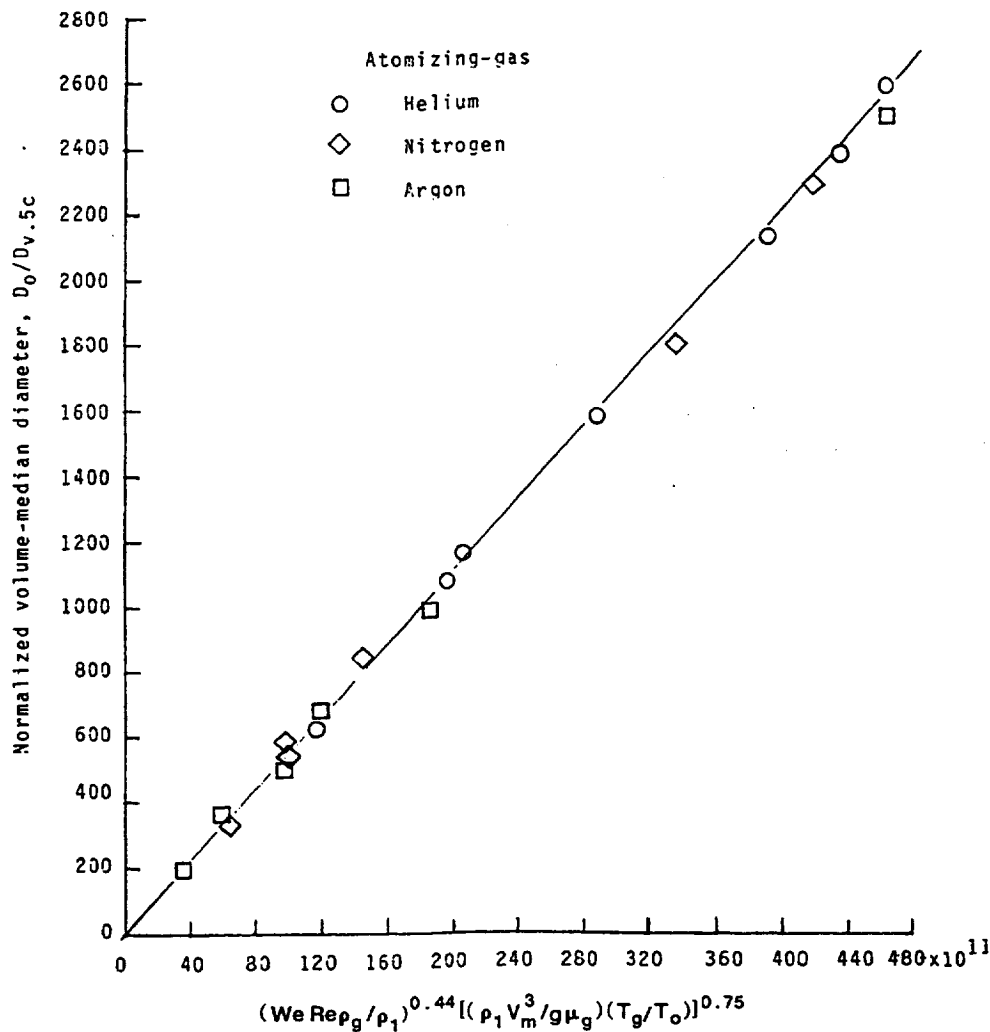Figure 8.—Correlation of $D_o/D_{v.5c}$ with dimensionless groups.

Figure 9.—Correlation of volume-median diameter, $D_{v.5c}$ with dimensionless groups.

where V_m is the RMS molecular gas-velocity and where the gas molecular-acceleration group is normalized with respect to the force due to gravitational acceleration, g.

To obtain a single correlating coefficient, $k'c$, for the three atomizing gases, $Do/D_{v.5c}$ is plotted against the three dimensionless ratios; WeRe $\rho l/\rho g$, $\rho l/V^3 m/g$ μg and Tg/To, as shown in Fig. 9. Thus, the following expression is obtained:

$$Do/D_{v.5c} = k'c(WeRe\ \rho l/\rho g^{0.44}[(\mu l\ V^3 m/g\mu g)(Tg\backslash To)]^{0.75}$$

(9)

where $k'c = 5.7 \times 10^{-11}$, for LN_2 jet breakup in high-velocity gasflows of He, GN_2 and Ar over a gas temperature range of 111 to 293 K.

CONCLUDING REMARKS

In the present study, an expression for cryogenic liquid jet breakup in two-fluid fuel nozzles was obtained that was valid over a wide range of atomizing-gas properties. Gas molecular weight and temperature were varied over ranges of 4 to 40 and 111 to 293 K, respectively. Also it should be noted that the two-fluid fuel nozzle used in this study is the same type of atomizer as that used in the RL^{-10} main rocket engines of the space shuttle.

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